LIFE

Self-consistent design considerations for commercial laser fusion energy

IFE Workshop, LLNL, 16 Nov 2021

Prof. Mike Dunne, Stanford University,
on behalf of the LIFE team (2008-2014)
mike.dunne@stanford.edu

The LIFE program integrated the work of a team of national labs, universities, industry and end-users

LLNL	Integrated plant & laser design
LANL	Tritium systems technology
SRNL	Tritium plant manufacturing and operations
PPPL	Gas handling system
GA	Target injection and manufacture
UIUC	Fusion chamber response
UCSD	Target survival and chamber design
UC Berkeley	Chamber performance
U Wisconsin	Chamber design
NPS	Structural materials

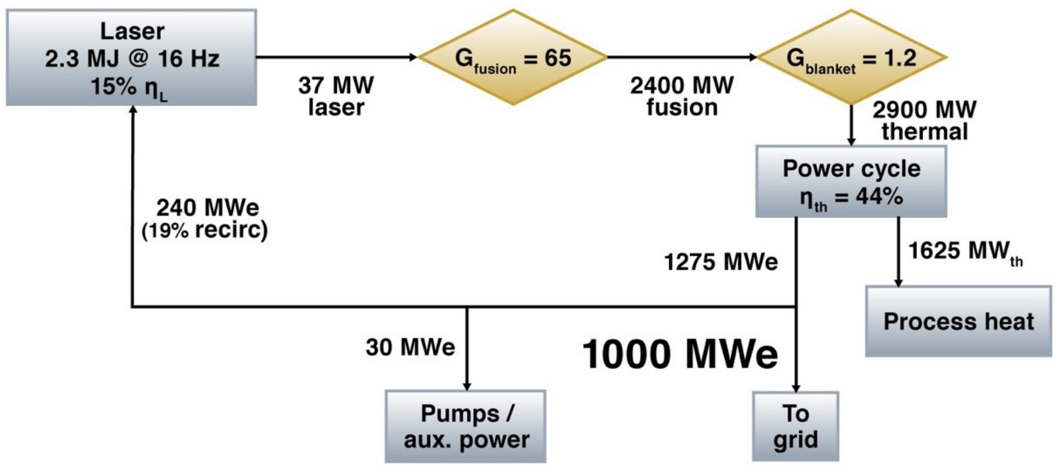
Plant, technology and materials development engaged over 80 vendor partners

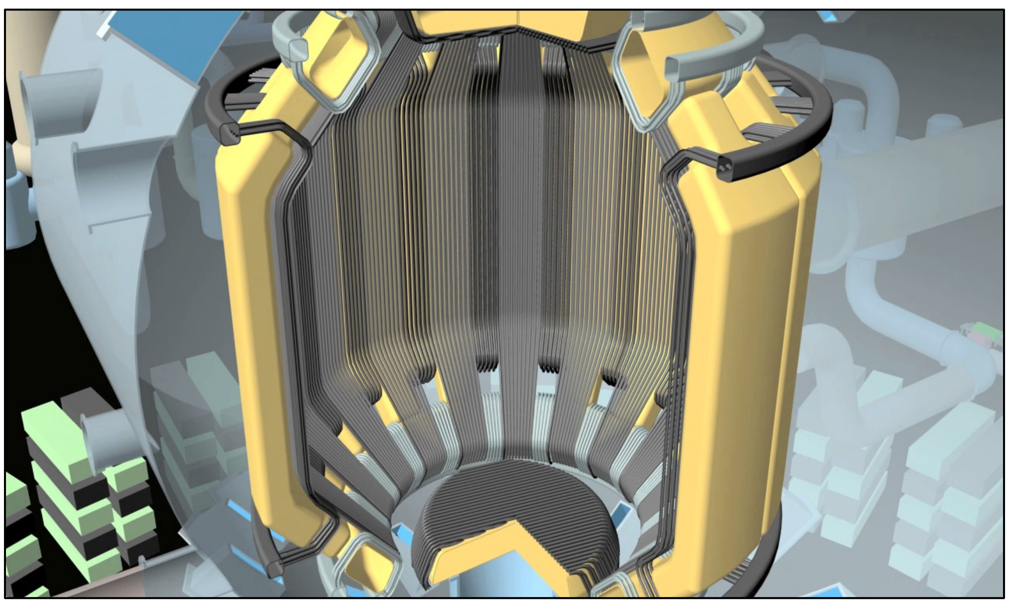
A broad group of end-users were consulted to determine the operational requirements for IFE

Utility requirements	Industry partnerships	Environment, policy, economics
LIFE advisory board formed by CEO / COO / CNOs from: • Exelon • Dominion • Entergy • Mid America • Pinnacle West • PG&E • Southern Company • Wisconsin Energy • SSEB	Power Plant Vendors Laser diode vendors Laser and optics vendors A&E construction firms Gas processing Remote Handling Control Systems Petrochemical industry	**Environmental and Sustainability groups** • EDF, BTI, GCEP, SERI, … **Nonproliferation** • NTI, CSIS, Belfer, CGSR **International** • JP, EU, CA, KR, RU, CN, Gulf states, … **Policy and Economics** • Bipartisan Policy Center • Howard Baker Forum • Oxford Economics • Pillsbury, Patton-Boggs

These end-user requirements drove major decisions on the plant design

Top level requirements: moving from physics and concepts to integrated solutions for the energy sector

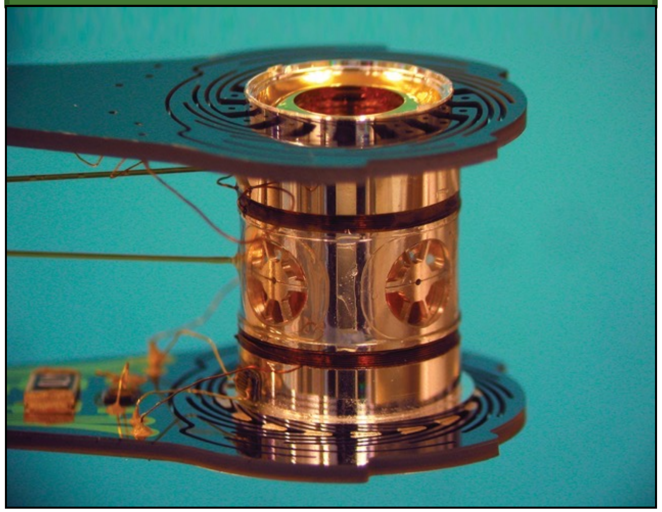




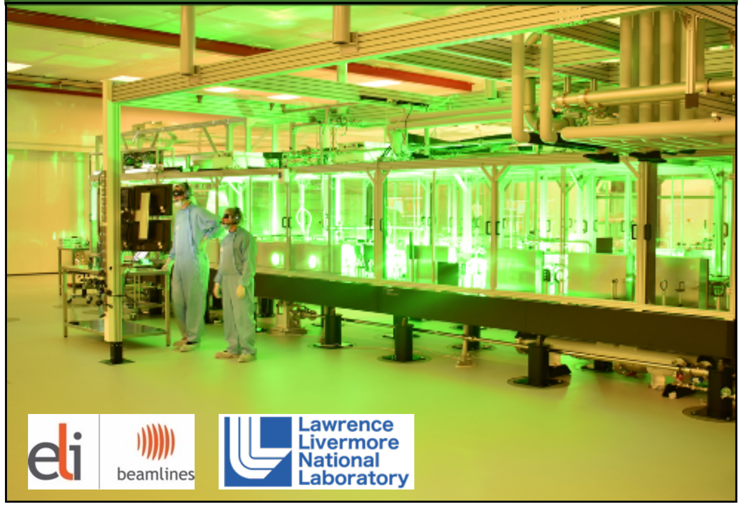
Plant Primary Criteria (partial list)
Cost of electricity
Rate and cost of build
Licensing simplicity / predictability
Acceptable waste stream
Meet urban environmental and safety standards (minimize grid losses)
Reliability, Availability, Maintainability, Inspectability (RAMI)
High capacity credit & load factor
Predictable shutdown & quick restart
Materials availability for a large fleet
Factory built systems
Conventional O&M personnel
Timely delivery & upgradeability

Addressing the end-user requirements 1/5: High assurance of performance

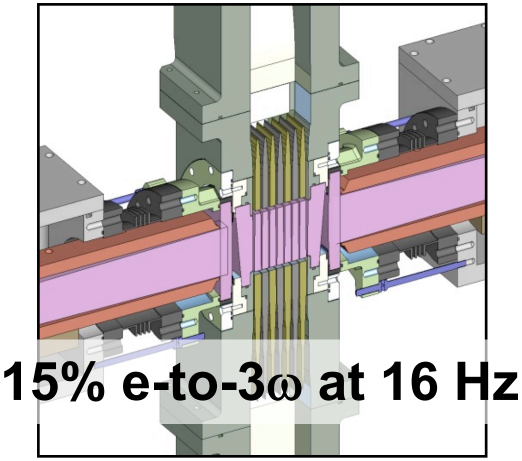
Driver: Fusion performance risk
Design: Testable on the NIF



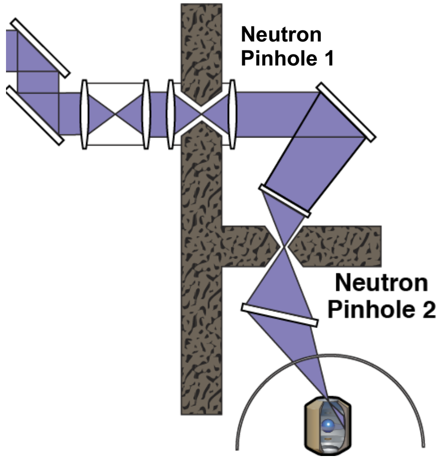
Driver: Robust laser ops (>kW, GShot)
Design: Multi-user architectures



Driver: System efficiency
Design: Diode-pumped lasers

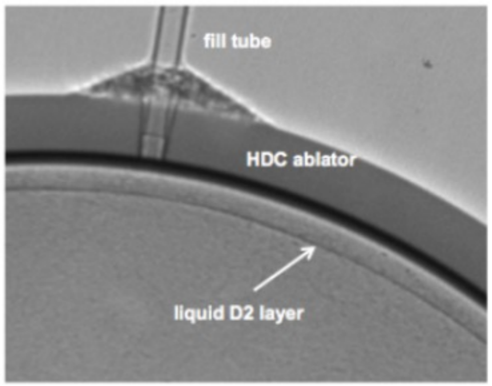


Driver: Maintainability & construction risk
Design: Dual pinholes, Decoupled optics



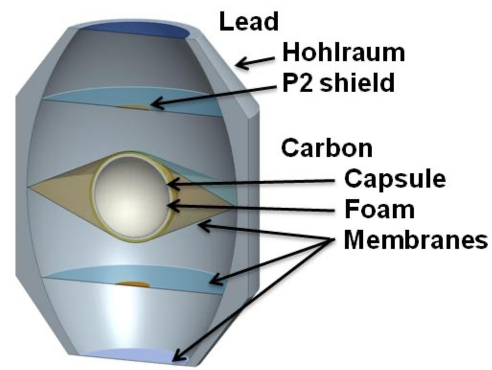
Addressing the end-user requirements
2/5: Fuel system delivery

Driver: Onsite Tritium inventory
Design: Wetted foams (no layering)

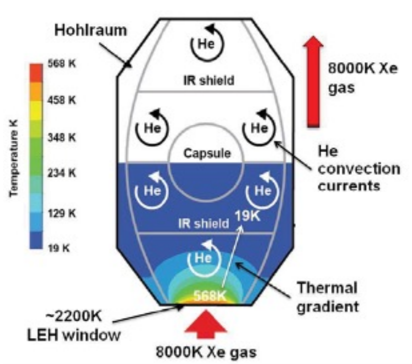


From: R. Olsen et al (LANL)

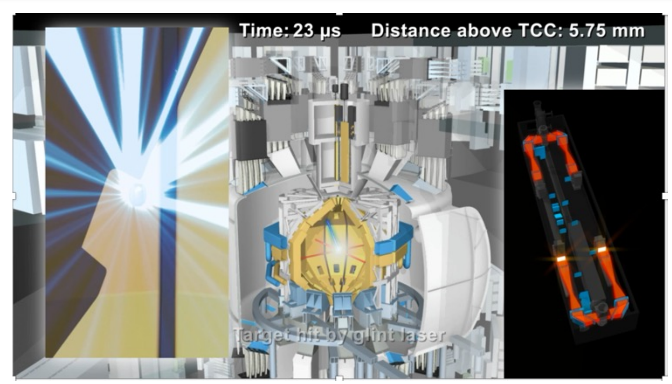
Driver: Chamber compatibility
Design: Pb hohlraum (no plating), Xe gas (ion, X-ray ranging) and Oxygen (exhaust)



Driver: Fuel integrity
Design: Thermo-mechanical shields



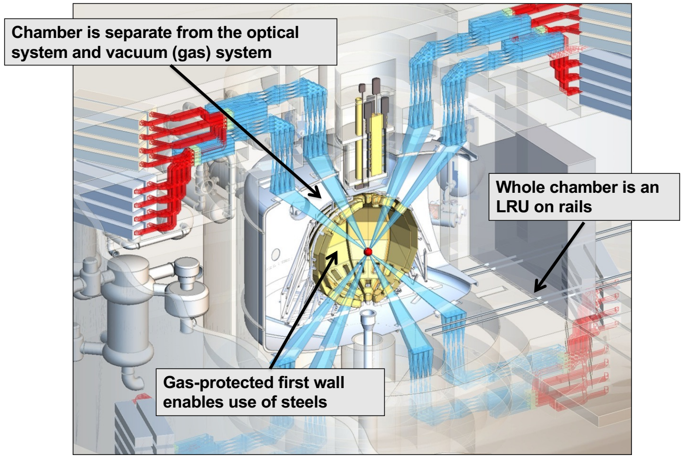
Driver: Reliable injection & engagement
Design: Glint triggers and steers the lasers



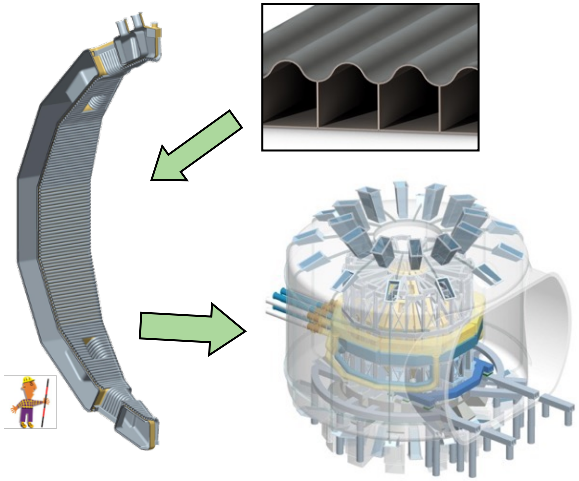
Manufacturing designs & tolerances need to be testable on the NIF

Addressing the end-user requirements
3/5: Chamber performance, survival and deployability

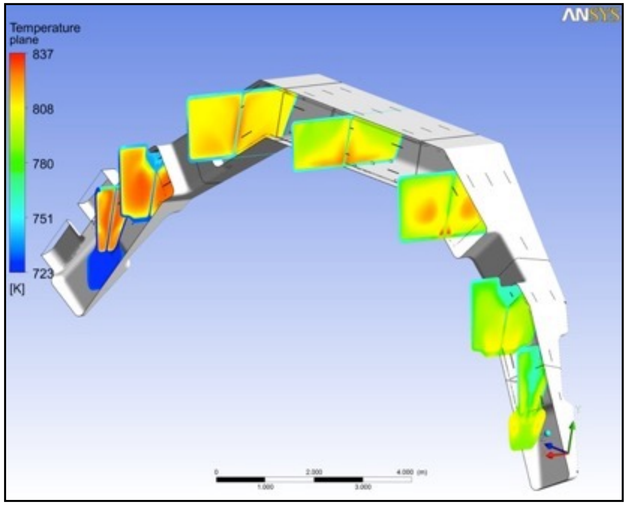
Driver: First wall lifetime
Design: Separate engine from chamber



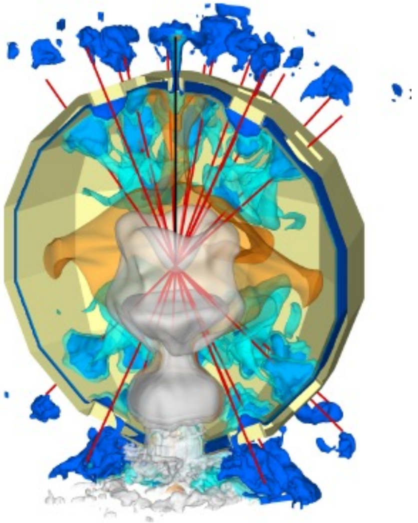
Driver: Regulatory approval (NRC, ASME)
Design: Conventional F/M steels



Driver: Thermal performance, corrosion
Design: Segmented wall and blanket

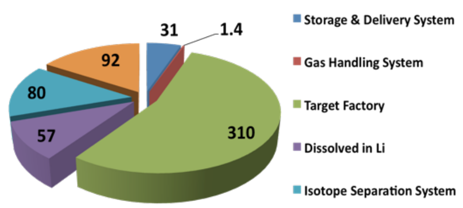


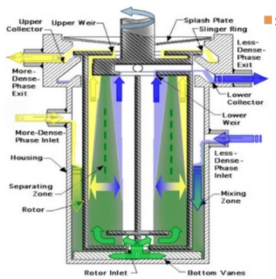
Driver: Chamber reset at 10 Hz
Design: Quasi-static 1% circulation



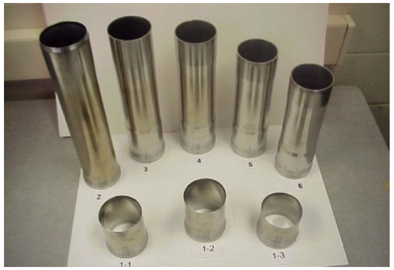
Addressing the end-user requirements 4/5: Attractive safety basis

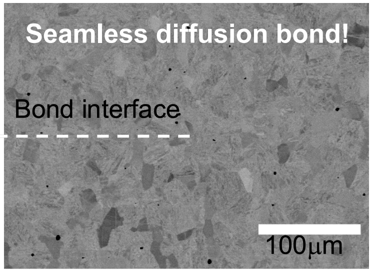
Driver: Low, segregated tritium inventory
Design: Liquid metal coolant





Driver: Class-A waste stream
Design: Low activation steel design

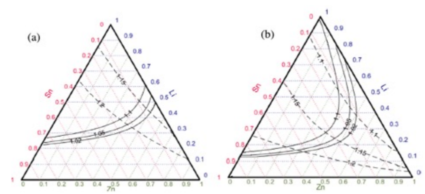




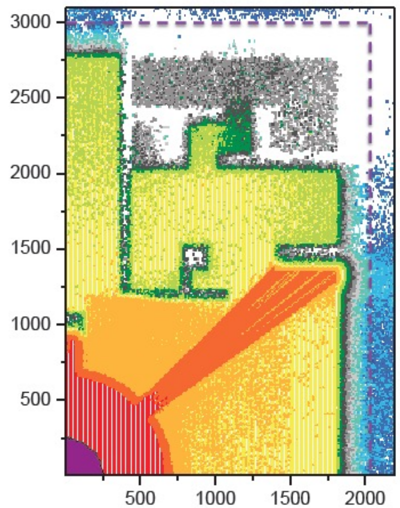
"LIFE-12" RA-FM steel
Waste Disposal Rating < 0.1

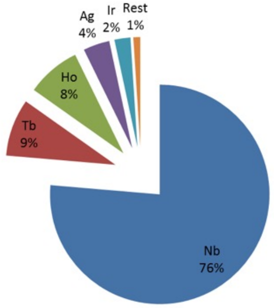
Driver: Offsite hazards
Design: Fuel design & Ternary alloys

Properties of Interest	Lithium	$Li_{17}Pb_{83}$	FLiBe	Ceramic*	*New Li Ternary*
Melt (C)	181	235	363	N/A	*<400*
Boiling (C)	1317	N/A	1430	N/A	*>1000*
Density (kg/m^3)	505	9500	1970	1600-3600	*1670*
Th. Cond. (W/m-K)	46	13	1	1-4	*53*
Specific heat (J/kg-K)	4260	188	2380	1176	*4930*
Tritium Permeation/ Separation issues	Low	High	High	High	*Med.*
Beryllium required	No	No	Yes	Maybe	*No*
^6Li enrichment	No	No	Maybe	Yes	*No*
Corrosion issues	Low	High	Med.	Low	*Low*
MHD issues	Yes	Yes	No	No	*Yes*
Chemical reactivity	High	Med.	Low	Low	*Med.*



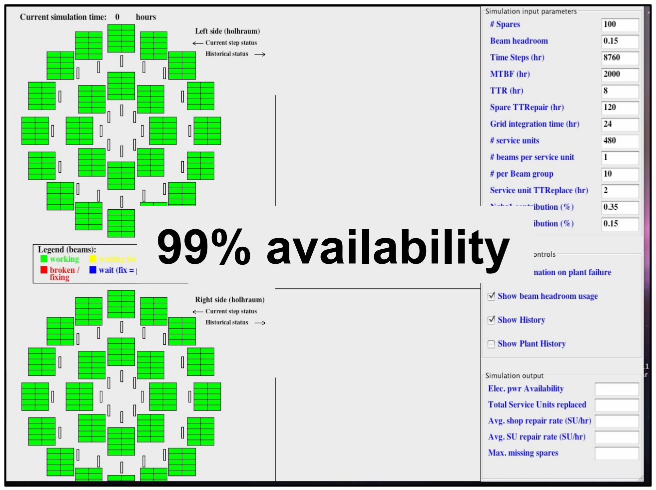
Driver: Low activation structures
Design: Separability of lifetime components



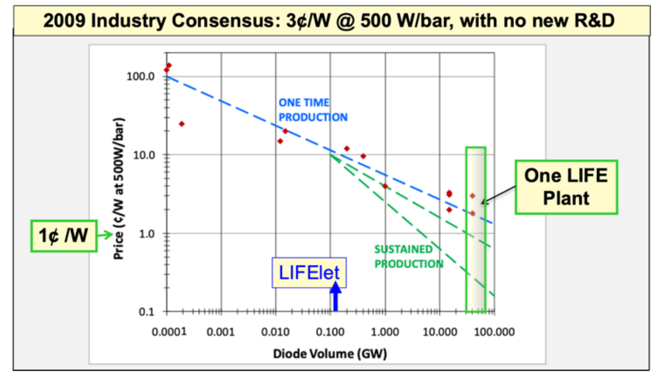


Addressing the end-user requirements
5/5: Plant economics & concept of operations

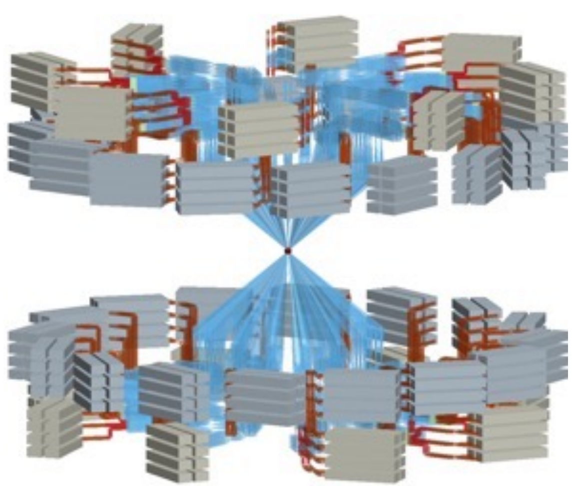
Driver: High availability for baseload
Design: Hot swappable lasers & optics



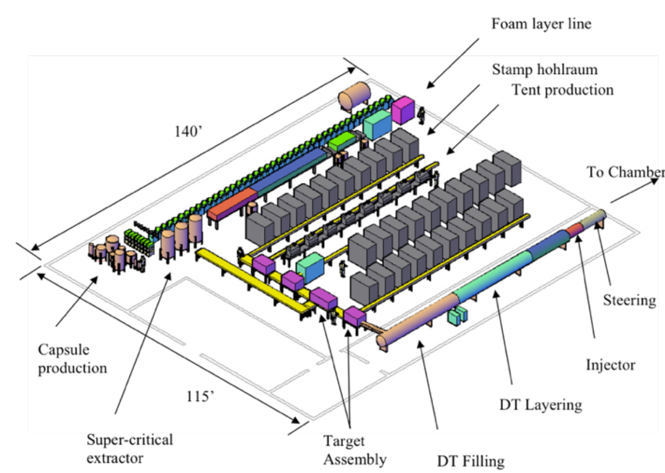
Driver: Capital cost
Design: Commercial components



Driver: Factory built systems
Design: Modular "LRU" designs



Driver: Operating costs
Design: Fuel mass manufacturing plant



Together, we need to assemble an integrated technical development plan that retires risk and ensures self-consistency

Issues		Consequence				
Fusion Physics			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Gain >60	M				
	On-the-fly ignition	H				
	>~99% probability of ignition	M				
	Target materials compatibilities	H				
Fusion Targets			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	DT layer in production environment	H				
	Target survival: injection, flight	H				
	Mass manuf: 400M/yr, <$1	H				
	Tritium Inventory-Target Filling	M				
Tritium Fuel Cycle			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Tritium Breeding Ratio	H				
	Recovery from Li	H				
	Recovery from Xe	H				
Target Injection and Tracking			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Accurate and repeatable in fusion env	H				
	Injector reliability in fusion env	M				
	Target survival in injector (fusion env)	H				
	Injector availability	M				
	Target tracking in fusion env	H				
Laser Fusion Driver			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Rep-rate operation	H				
	Final optic survival	H				
	Electrical efficiency	L				
	Target engagement	H				
	Focal spot consistent with LEH	H				
	Laser system availability	M				
Fusion Engine			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	First wall radiation damage survival (FMS) 10 dpa	H				
	First wall radiation damage survival (ODS) 50 dpa	M				
	Chamber clearing	H				
	Debris management-from chamber outlet	H				
	Heat Transport - from chamber outlet	M				
	Thermal and mechanical insults	H				
	Corrosion	M				
	Chamber Design consistent with Fabrication	M				
	Availability	M				
	Concept of chamber replacement	M				
	Production capability for Chamber Materials (FMS)	M				
	Production capability for Chamber Materials (ODS)	M				
Power Conversion Systems			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Tritium release through Rankine cycle	M				
Licensing and Regulatory			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Licensing strategy	H				
	Auth for initial ops	H				
	NRC license for ComOps	H				
	Regulator approval of waste streams	H				
Integrated Site Operations			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Concept of operations	M				
	Concept of maintenance	M				
	Personnel requirements	M				

The ability to access the NIF, and the separability of many technical subsystems provides an attractive basis for a national IFE program in the US

Areas for priority technology development include…

- Tritium processing systems (from gas, liquid metals, …)
- Target (fuel) manufacturing processes
- Coolant loop materials: corrosion, impurities, chemical reactivity, …
- Structural materials: impurity levels for bulk production, cyclic stresses, …
- Chamber gas/liquid chemistry (recovery, waste, clogging)
- Final Optics survival and hot-swap changeout
- Injection, tracking, engagement, and timing systems

… in addition to the underpinning target and driver performance developments

It is important to recognize the scale and connectivity of the technical challenges ahead …

- Over a dozen integrated IFE power plant design studies have been performed.
- Along with a wide range of individual technology development activities.
- Many areas of commonality with MFE, HEDS, and commercial applications.
- **Any new IFE program should balance the need for breadth and innovation with the imperative for rigorous self-consistency of design solutions**.

Inertial Confinement Fusion Power Plants

Mike Dunne[a], **Tom Anklam**[b,*], **and Wayne Meier**[b,*], [a]SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA, United States; [b]Lawrence Livermore National Laboratory, Livermore, CA, United States

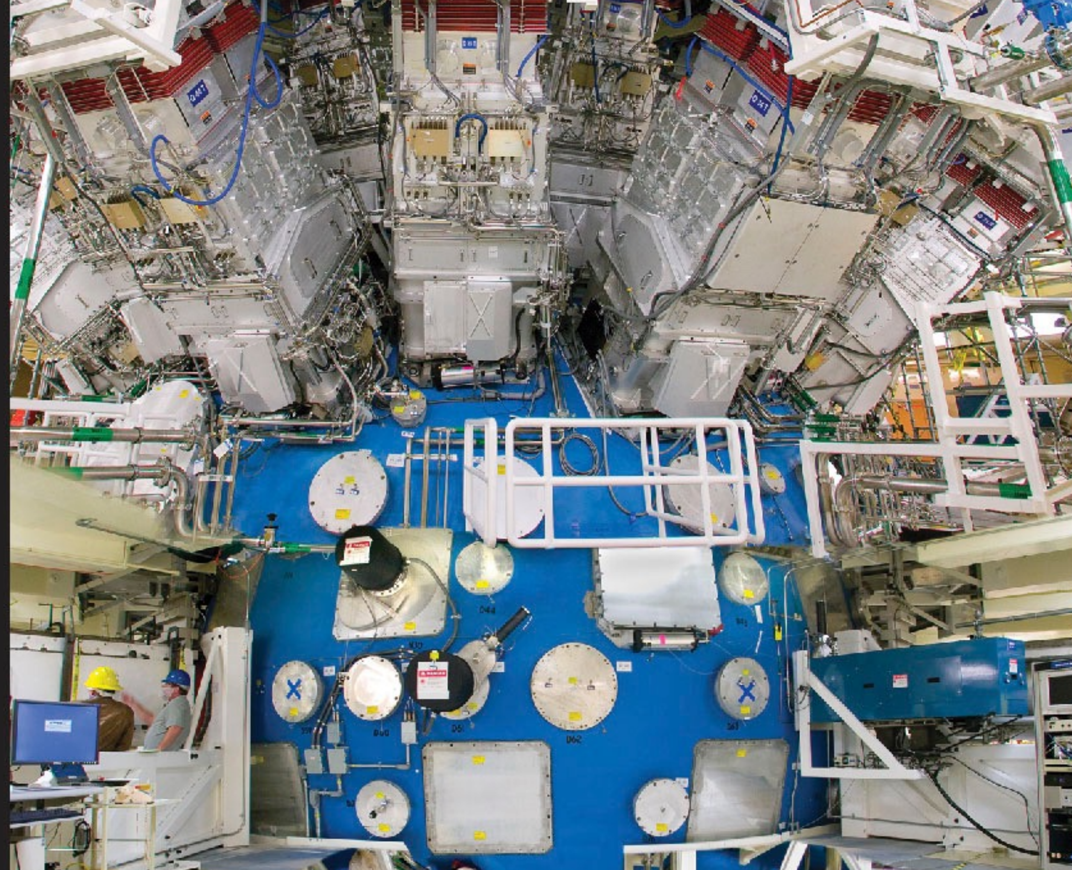
Table 1 Key fusion engine parameters.

	Year	*Driver energy, MJ*	*Driver eff., %*	*Target gain*	*Target yield, MJ*	*Pulse rate, Hz*	*Fusion power, MW*	*Chamber first wall material*	*Chamber structural material*	*Breeding material*
Heavy ion beam driven										
Osiris	1992	5.0	28.2	86.5	432	4.6	1987	C fabric	C	FLiBe
Prometheus-H	1992	7.0	18.5	103	719	3.54	2543	SiC	SiC	Li_2O
HYLIFE-II	1994	5.0	35	70	350	6.0	2100	Steel	Steel	FLiBe
Laser driven										
Sombrero	1992	3.4	7.5	118	400	6.7	2677	SiC	SiC	Li_2O
Prometheus-L	1992	4.0	6.5	124	497	5.65	2807	SiC	SiC	Li_2O
LIFE	2011	2.2	15.8	60	132	16.7	2200	Steel	Steel	Li
Z-pinch driven										
Z-IFE (10 chambers)	2006	30	15	100	3000	0.1	3000	Steel	Steel	FLiBe

Table 2 Key power plant parameters.

	Primary coolant	*Primary coolant Tmax, C*	*Plant eff., %*	*Thermal power, MWt*	*Gross electric power, MWe*	*Driver power, MWe*	*In-plant power, MWe*	*Net electric power, MWe*	*Plant gain*
Heavy ion beam driven									
Osiris	FLiBe	650	45	2504	1127	82	45	1000	7.9
Prometheus-H	Pb & He	525 (Pb) 650 (He)	42.7	2780	1189	137	53	999	5.3
HYLIFE-II	FLiBe	650	43	2500	1075	85	50	940	7.0
Laser driven									
Sombrero	He + Li_2O	700	47	2891	1359	304	55	1000	2.8
Prometheus-L	Pb & He	525 (Pb) 650 (He)	42.3	3264	1382	349	61	972	2.4
LIFE	Li	575	47	2640	1217	248	64	905	2.9
Z-Pinch driven									
Z-IFE	FLiBe	680	43	3572	1536	200	71	1264	4.7

Let's ensure we take full advantage of the extensive work performed to date



National Academies (2013) *Conclusion 4-13, “The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be **when ignition is achieved**.”*

The LIFE team at LLNL (circa 2011)

References

M. Dunne, T. Anklam, W. Meier, "*Inertial Confinement Fusion Power Plants*", Encyclopedia of Nuclear Energy, Elsevier, https://doi.org/10.1016/B978-0-12-819725-7.00170-7 (2021)

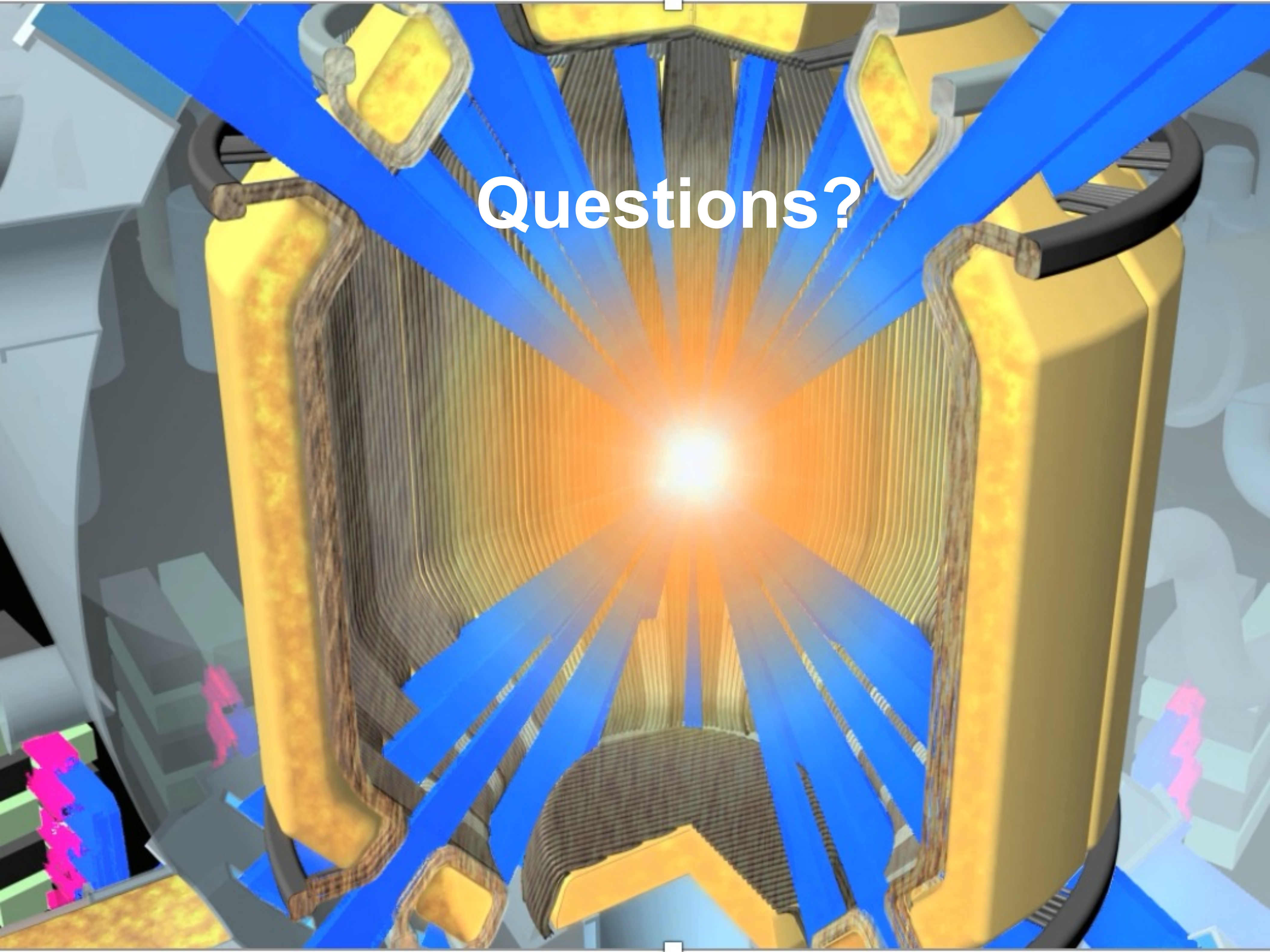
M. Dunne, et al., "*Timely Delivery of Laser Inertial Fusion Energy*", Fusion Science and Technology 60, 19-27 (2011)

A. Bayramian, et al., "*Compact, efficient laser systems required for laser inertial fusion energy*", Fusion Science and Technology 60, 28-48 (2011)

P. Amendt, et al., "*LIFE pure fusion target designs: status and prospects*", Fusion Science and Technology 60, 49-53 (2011)

J. Latkowski, et al., "*Chamber design for the laser inertial fusion energy (LIFE) engine*", Fusion Science and Technology 60, 54-60 (2011)

R. Miles, et al., "*Challenges surrounding the injection and arrival of targets at LIFE fusion chamber center*", Fusion Science and Technology 60, 61-65 (2011)"


Questions?